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Broad-band colour evolution of star clusters

Léo Girardi

Dipartimento di Astronomia, Università di Padova
Vicolo dell'Osservatorio 5, I-35122 Padova, Italy

Abstract. We briefly review the main features in the broad-band colour evolution of star clusters, over the complete age interval from 10^7 to 10^{10} yr. The emphasis is in the problem of age-dating distant young clusters ($\lesssim 2$ Gyr) from their integrated colours. It is shown that $U-B$ and $B-V$ are less sensitive to metallicity than colours involving red pass-bands, like $V-I$, at least up to ages of some few Gyr. Since $U-B$ and $B-V$ are determined by well-understood and well-populated evolutionary stages, they are also less affected by theoretical uncertainties and by the ubiquitous effect of stochastic colour dispersion. The latter effects become important for the $V-K$ colour. Thus, we argue that $U-B$ and $B-V$ are, presently, the more suitable broad-band colours for age-dating distant clusters. For other potentially useful colours like $V-R$ and $V-I$, empirical tests of their evolution are still missing.

1. Introduction

The basic properties of distant star clusters, like ages, metallicities, or masses, can be derived only from integrated spectral properties. The obtention of spectra with reasonable S/N ratio is, in general, prohibitive for galaxies located outside the Local Group (but for some few exceptions, e.g. NGC 7252; Schweizer & Seitzer 1998). It follows that *broad-band magnitudes and colours are the primary source of information about masses and ages of distant star clusters*. Up to recently, this was true even for the relatively nearby Magellanic Cloud (MC) clusters. We point out that from a total of about 2400 LMC clusters, only about 300 have ages derived directly from the features in the colour-magnitude diagram (CMD), whereas 600 have them estimated from the colours (Bica et al. 1996; Girardi et al. 1995). This latter situation is however rapidly changing, as massive and high-quality photometric data become available for the MCs.

In most papers in the field, the ages of distant star clusters are estimated by a simple comparison of the observed colours with those predicted by a set of population synthesis models. As simple and easy-to-apply this approach is, it is not demonstratedly the best one. In fact, for the nearby LMC clusters, empirical or semi-empirical methods have so far been preferred, and we are not aware of recent works in which the LMC clusters are age-dated from a direct comparison between model and observed colours. Some of the reasons for this will be mentioned in the following.

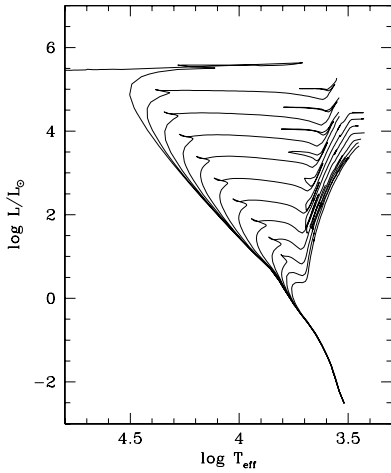


Figure 1. Evolution of theoretical isochrones for solar metallicities ($Z = 0.019$). They are derived from the Girardi et al. (2000; for $M \leq 7 M_{\odot}$) and Bertelli et al. (1994; for $M > 7 M_{\odot}$) databases of stellar tracks. The TP-AGB phase is from Marigo et al. (1999). From above to below, the $\log t$ values go from 6.66 to 10.33 (with t in yr), at intervals of $\Delta \log t = 0.33$.

2. Theoretical grounds

The HR diagram of Fig. 1 shows a sequence of isochrones at equally-spaced intervals of the logarithm of the age, $\log t$. From this figure it is evident that both $\log L$ and $\log T_{\text{eff}}$ of the turn-off stars fade at an almost constant rate with $\log t$. This is a simple consequence of the mass–luminosity relation of main sequence (MS) stars being a power-law. Core-helium burning (CHeB) stars follow the same linear trend in $\log L$, but only up to ages ~ 1 Gyr. These trends determine, to a large extent, the main features of the evolution of integrated magnitudes: if the initial mass function is also a power law (e.g. the Salpeter one), one expects an almost constant rate of fading of magnitudes with $\log t$.

And in fact, this is the case for the blue–visual pass-bands, like UBV , which depend mostly on the behaviour of stars in the stages of MS termination and CHeB. The roughly linear fading of M_U , M_B , M_V , and M_R with $\log t$ (with slope ~ 2 mag/dex) is shown in Fig. 2. The same behaviour holds for the near-ultraviolet evolution (e.g. the 1550 pass-band), but only up to an age of $\sim 10^8$ yr; after that, turn-off stars are too cold to contribute to the UV spectra.

The situation becomes different in the red and near-infrared. Evolved stars such as red supergiants (RSG), asymptotic giant branch (AGB) and first-ascent red giants (RGB) determine the evolution at these wavelengths. Since the number of these stars is a strong (and non-monotonic) function of $\log t$, the resulting magnitude and colour evolution is also complicated. This can be seen in Fig. 2: in I and more clearly in JHK , the evolution is marked by the RSGs at $\gtrsim 10^7$ yr, and by the presence of AGB stars at $> 10^8$ yr. Between $\log t \simeq 8$ and 9.3, the details of the colour evolution are essentially determined by AGB stars. At $10^{9.2}$ yr, a transient red phase appears due to the increased number of AGB stars which temporarily follows the onset of the RGB (Girardi & Bertelli 1998).

3. Trends with metallicity

The above picture is valid for near-solar metallicities. Going to lower metallicities, some of the trends are just obvious: for the same $\log t$, colours get

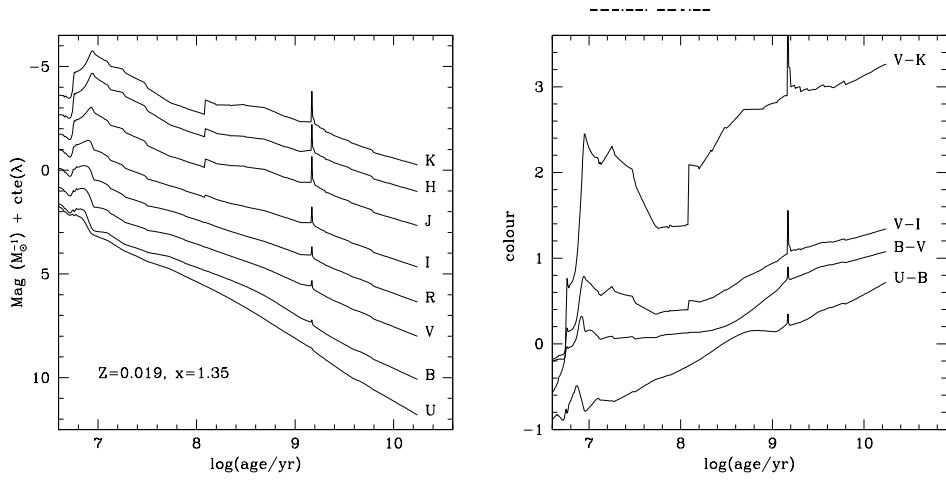


Figure 2. Evolution of integrated broad-band magnitudes (left panel), and colours (right panel) with $\log t$, for $Z = 0.019$, and a Salpeter IMF. The curves in the left panel have been shifted by integer quantities, in order to avoid their superposition.

bluer. However, this effect is much larger at ages ≥ 2 Gyr, and for the red and near-infrared pass-bands. This is shown in Fig. 3, with the colour evolution at different metallicities. For a large age interval, $7.3 < \log t < 9.2$, $U-B$ and $B-V$ colours differ by less than 0.15 mag for metallicities in the interval $0.004 < Z < 0.019$. Moreover, the $U-B(t)$ and $B-V(t)$ relations are virtually monotonic. It follows that $U-B$ and $B-V$ are good age indicators, provided that $B-V \lesssim 0.6$ and $U-B \lesssim 0.2$.

The metallicity dependence of colours gets larger at ages $\log t > 9.3$, when subgiant and RGB stars become important in comparison with MS and CHeB ones. This is the range of the age-metallicity degeneracy: ages can be estimated only if independent information on metallicity is provided, and vice-versa.

At low metallicities, the RSG red phase is practically missing, and AGB and RGB phases develop at higher temperatures. This results in small changes in the behaviour of $U-B$ and $B-V$ colours, which are, fortunately, of low entity for most of the age interval, i.e. $7.3 \lesssim \log t \lesssim 9.2$. In the IJK pass-bands the changes become remarkable, since these stars are the main contributors to the red and near-infrared flux. It comes out that colours like $V-I$ and $V-K$ are very dependent on the way AGB stars are considered in the models (see Girardi & Bertelli 1998). Moreover, the colour-age relation is not monotonic for $V-I$ and $V-K$. Thus, when taken separately from other colours, they are not good age indicators.

A remark is worth here. It is often assumed that all models of population synthesis predict equally well the evolution of broad-band colours, since they are, in general, based on the same sets of evolutionary tracks and synthetic spectra. This is not exactly true. One important source of difference between models is on the way different groups consider the thermally pulsing AGB phase. In some cases, TP-AGB stars are even neglected; this is a bad assumption since up to 50 % of the bolometric luminosities, at certain ages, come from

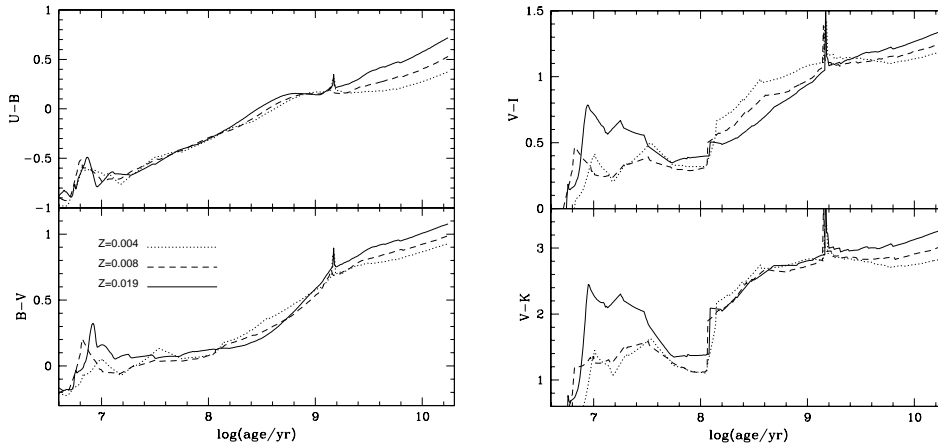


Figure 3. Evolution of $U-B$, $B-V$ (left panel), $V-I$, and $V-K$ (right one), with $\log t$, for metallicities $Z = 0.004$, 0.008 , and 0.019 .

these stars (cf. Frogel et al. 1990). In other cases, TP-AGB stars are included according to some empirical prescription, as e.g. that derived from the Frogel et al. (1990) observations of AGB stars in MC clusters. Although apparently better, this latter approach does not include any metallicity dependence in the TP-AGB evolution, whereas every single aspect of this evolution (mass loss, dredge-up, hot-bottom burning, lifetimes) is expected to be strongly dependent on metallicity¹. The best approach, probably, is to use TP-AGB models whose parameters have been calibrated in order to reproduce the properties of AGB stars in the MCs, like those by Van der Hoek & Groenewegen (1997) and Marigo et al. (1999). The latter ones are adopted here.

For near-solar metallicities, TP-AGB stars affect mainly the red and near-infrared passbands (e.g. IJK) and colours like $V-I$ and $V-K$. At low metallicities, TP-AGB stars slightly affect also the visual colours, like $B-V$ and $V-R$ (see Girardi & Bertelli 1998). These are the colours and metallicity ranges in which different population synthesis models may differ the most. We point out that the metallicity dependence of $V-K$ is almost absent in the $\log t > 8$ models of Fig. 3, just *because* the underlying TP-AGB models include a considerable dependence on this parameter, which compensates for the changes in the mean AGB temperature. Different trends would be found in other models.

4. The problem of age determination

A variety of effects, other than age and metallicity, determine the integrated colours of star clusters. A very subtle and ubiquitous one is that of “stochastic fluctuations” in the integrated colours due to the limited number of stars. The effects are sizeable already in $B-V$ colours, even for the populous LMC clusters

¹These dependences, even when not explicitly included in the equations of TP-AGB evolution, come naturally from the changes in the typical temperatures of AGB envelopes with metallicity.

which have $M_V \lesssim -6$. For $M_V = -6$, the standard deviation of $B-V$ varies from $\sigma(B-V) \simeq 0.25$ at $\log t = 7.3$, to $\sigma(B-V) \simeq 0.03$ at $\log t = 9.0$ (Girardi et al. 1995). It scales approximately as $\sigma(B-V) \propto 0.7^{-M_V}$.² Thus, only for intermediate-age clusters, and for young ones with $M_V \lesssim -9$, is this intrinsic dispersion lower than that caused by cluster-to-cluster metallicity variations of $\sigma([\text{Fe}/\text{H}]) \simeq 0.3$ dex.

In contrast, more dramatic stochastic fluctuations are found in the red and near-infrared pass-bands, due to the sampling of a small number of luminous red stars per cluster (e.g. the AGB ones; see Santos & Frogel 1998; and Lançon, this meeting). Also in this respect, the blue-visual pass-bands do a better job than red and near-infrared passbands, since they sample the light coming from stars in well-populated evolutionary stages.

To summarize, colours such as $B-V$ and $U-B$ present several potential advantages for the age determination of young clusters, as the lower sensitivity to metallicity, stochastic fluctuations, and their monothonic behaviour with age. In fact, the most classic way to determine the ages of MC clusters from colours, namely the Elson & Fall (1985; EF) one, makes use of the $B-V$ versus $U-B$ two-colour plane. Clusters draw a fairly regular S -shaped curve in this plane, so that their position along this curve simply indicate their $\log t$ values. The EF method has been slightly modified by Girardi et al. (1995) in order to take into account the fact that the 3 most important factors of dispersion of colours at fixed age – namely the metallicity, reddening, and stochastic dispersions, – act in almost the same direction in the two-colour plane. However, it has been demonstrated that the age determinations with the EF method become unreliable for clusters older than say 4 Gyr, due to the age-metallicity degeneracy above mentioned.

The EF method has the advantage of being empirical, since the age sequence of clusters in the two-colour plane is calibrated using LMC clusters with ages directly determined from the CMD features. In this way, uncertainties in the integrated colours of models (always present and of order 0.05–0.1 mag in UBV) do not affect age estimates. Determinations of $\log t$ obtained this way present accuracies of 0.15 dex, at least for the most populous LMC clusters (Girardi et al. 1995). We remark that, using a simple comparison between the LMC cluster colours and population synthesis models, the typical accuracies would be much worse, i.e. $\sigma(\log t) \sim 0.3$ dex. The validity of the EF method has also been confirmed for SMC clusters by Grebel et al. (1999).

Considering these aspects, it is surprising that empirically-calibrated methods are rarely used (and exceptions are e.g. Bresolin et al. 1996; and Larsen & Richtler 1999) for the age-dating of distant clusters. Moreover, very often are the ages of distant clusters derived from $V-I$ or $V-K$, which, from a theoretical point of view, are not the most appropriated colours. To be more specific, the age information these colours contain is poorer than that contained in a single measure of $B-V$ and/or $U-B$, because of the effects of non-monotonicity with $\log t$, metallicity dependence, and/or stochastic dispersion. For $V-K$, the importance of these effects can be confirmed by simply looking at the way $V-K$

²Notice that, in Eq. 3 of Girardi et al. (1995), the exponent is presented with the wrong sign. The correct equation should read $\dots \times 0.7^{-(M_V+6)}$.

colours change among clusters of similar age in the LMC (Santos & Frogel 1998; Girardi & Bertelli 1998). More compelling reasons for avoiding the red pass-bands in age determinations, can be derived from population synthesis models. One finds that the predicted $V-I$ and $V-K$ colour evolution can differ appreciably from author to author, as a result of the different ways in which the several models include the TP-AGB evolutionary phase. This uncertainty is not present in the UBV pass-bands.

However, it is also true that most modern instrumentation, and the strong absorption met in several interesting galaxies, favour the observations in pass-bands like $VRIK$, instead of the UBV necessary for easy age determinations. Measuring clusters in red pass-bands is, in many cases, a necessity.

The $BVRI$ pass-bands are, probably, those in which the best data for distant clusters are available. To improve upon the age estimates obtained from these data, it would be advisable to test, empirically, the age and metallicity dependences of the $V-R$ and $V-I$ colours. We notice that this can be done, to some extent, using the present-day photometric databases for MC clusters (e.g. OGLE, MACHO, and the MC Photometric Survey; see the contributions in Chu et al. 1999). Only after these behaviours are well documented, will we be able to check the reliability of such age determinations. Also, this kind of work may constitute an important test to models of spectral evolution of stellar populations, regarding, especially, the way they include (or do not) the latest evolutionary phases for different metallicities.

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